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Corrosion Inhibition of Mild Steel Using Green Synthesized Tungsten Oxide Nanoparticles in Acidic Media

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ABSTRACT

Corrosion is a serious problem in industrial applications, and therefore the need to produce environmentally friendly inhibitors. The current research examines the corrosion inhibition performance of eco-synthesized tungsten oxide nanoparticles (WO_3 NPs) derived from Cassia fistula leaf extract as an inhibitor for mild steel in 1M HCl. Characterization confirmed the successful synthesis of the WO_3 NPs with a granular, closely packed nature. Weight loss measurements revealed that corrosion rates decreased significantly with an increase in the concentration of the WO_3 NPs, with an inhibition of over 85% being achieved with 200 ppm. Electrochemical measurements including cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) revealed enhanced charge storage capacity, an increase in the charge transfer resistance, and a decrease in the corrosion current density. Potentiodynamic polarization studies corroborated the positive shift in the corrosion potential and a great reduction in the current density from 1.2×10^{-3} A/cm² (control) to 2.8×10^{-5} A/cm² with 500 ppm of the WO_3 NPs, demonstrating the immense protective effect of the NPs. Scanning electron microscopy (SEM) revealed a uniform development of a protective layer over the steel surface that prevents the direct acid attack and decreases pitting. The inhibition performance of the WO_3 NPs was comparable to or better than the conventional inhibitors but with eco-friendliness. These findings support the use of the biosynthesized WO_3 NPs as a promising sustainable alternative to the protection of corrosion in an acid environment with potential industrial applications.

Keywords: Corrosion inhibition, tungsten oxide nanoparticles, Cassia fistula, electrochemical studies, green synthesis, mild steel protection.

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I. INTRODUCTION

Corrosion is a global problem that affects industries such as construction, transportation, and energy. Corrosion is estimated to cost the global economy 3–4% of the world's Gross Domestic Product (GDP), equivalent to billions of dollars in economic losses (Etsuyankpa et al., 2024). Corrosion leads to failures of structures, safety issues, and increasing maintenance costs, necessitating effective preventive strategies.

Industrial use of mild steel, which possesses mechanical strength and is economical, also renders it vulnerable to corrosion, particularly in the presence of acids (Alghamdi, 2023). Corroded steel structures do not only cause economic losses but also pose environmental hazards in the form of material degradation and chemical leaching into the ecosystem. Thus, it is important to create effective, eco-friendly corrosion inhibitors to extend the life of the metal infrastructure and reduce maintenance costs.

Traditional corrosion inhibitors, including synthetic inorganic and organic compounds, have traditionally been used to avoid the degradation of the metal. They prevent corrosion by forming a protective layer on the metallic surface, thereby reducing its exposure to the corroding environment (Hassin & Salman, 2022). The majority of the conventional inhibitors, however, comprise harmful chemicals like chromates, phosphates, and nitrites that have serious environmental as well as human health consequences (Pais et al., 2021).

Due to such problems, regulatory agencies have introduced strict limits on the use of harmful corrosion inhibitors, calling for greener alternatives to be developed (Monikandon & Ravisankar, 2024). Initiatives to study environmentally friendly corrosion inhibitors that are biodegradable, non-toxic, and sustainable have now taken the lead.

Nanoparticles have proven to be effective corrosion inhibitors owing to their physicochemical characteristics, such as high surface area, reactivity, and capacity to create protective layers on the surface of metals. Various forms of nanoparticles, such as metal oxides, carbon-based nanomaterials, and polymer nanocomposites, have been considered for corrosion protection (Etsuyankpa et al., 2024). Nanoparticles adhere to the surface of the metal, forming a protective layer that shields it from contact with corrosive substances (Alghamdi, 2023). Metal oxide nanoparticles promote the development of passive layers, which suppress oxidation reactions (Keskin et al., 2021). Nanoparticles increase the effectiveness of traditional corrosion inhibitors by enhancing the adhesion and distribution of the latter on the surface of the metal (Gouda & El-Lateef, 2021).

Studies have shown that metal oxide nanoparticles such as zinc oxide, cerium oxide, and tungsten oxide possess excellent corrosion inhibition due to the fact that they exhibit high chemical stability and the ability to interact with metallic surfaces (Hassin & Salman, 2022).

Among the oxides of metals, tungsten oxide (WO_3) nanoparticles have also drawn attention since they have good corrosion resistance, chemical stability, and non-toxic nature (Owoeye et al., 2024). Yet, the conventional method of synthesis of WO_3 particles requires the use of harmful chemicals and energy-intensive operations.

Green synthesis presents an environmentally friendly alternative by using the extracts of plants as a reducing and stabilizing agent in the process of nanoparticle synthesis. Cassia fistula, a pharmacologically active plant with rich bioactive compounds, is extensively applied in the field of green nanotechnology owing to its richness with flavonoids, tannins, alkaloids, and phenolic compounds (Danish et al., 2022). These bioactive compounds help to reduce the metal ions and serve as a capping agent to increase the stability of the nanoparticle and avoid agglomeration (Abaid et al., 2023).

Recent studies have indicated the successful synthesis of various metal nanoparticles with the aid of Cassia fistula extracts. Cassia fistula synthesized silver and copper oxide nanoparticles have indicated successful

antimicrobial and antioxidant activity, hence substantiating its use in corrosion inhibition as well (Veeramani et al., 2022). The ability of Cassia fistula to stabilize the oxide of the metals makes it a potential candidate for the green synthesis of the environmentally friendly WO_3 nanoparticles that have the capability to serve as effective corrosion inhibitors.

Although a lot of research on corrosion inhibition has been carried out, the corrosion inhibition potential of green-synthesized WO_3 nanoparticles is not fully explored. Most research on corrosion inhibition has centered on chemically synthesized inhibitors, ignoring the environmental effects of such processes (Monikandon & Ravisankar, 2024).

The current study is centered on the green synthesis of tungsten oxide nanoparticles using Cassia fistula extract and the evaluation of their effectiveness as mild steel corrosion inhibitors.

II. MATERIALS AND METHODS

2.1 Preparation of Tungsten Oxide Nanoparticles (WO_3 NPs)

2.2.1 Biosynthesis Using Cassia fistula Extract

The green synthesis of tungsten oxide nanoparticles (WO_3 NPs) was carried out using Cassia fistula leaf extract as a reducing and stabilizing agent. Fresh Cassia fistula leaves were washed with distilled water, air-dried for a week, and powdered. The dry leaf powder was extracted with deionized water at 60°C for 2 hours. The extract was filtrated using Whatman No. 1 filter paper and stored at 4°C to use subsequently (Danish et al., 2022).

A precursor solution of sodium tungstate (Na_2WO_4) was prepared and mixed with the plant extract with stirring at room temperature. The reaction mixture was heated at 80°C for 3 hours until a color change was observed, indicative of the precipitation of tungsten oxide nanoparticles (Owoeye et al., 2024). The synthesized nanoparticles were centrifuged at 10,000 rpm for 15 minutes, washed with ethanol and deionized water, and dried at 100°C before characterization (Beddiar et al., 2024).

2.2 Mild Steel Sample Preparation

Specimens of mild steel with the size of 3 cm × 3 cm × 0.2 cm have been utilized to examine the inhibition of corrosion. The samples have been mechanically polished with silicon carbide papers of 1000 grit size, washed with distilled water, degreased with acetone, and dried in room temperature before being immersed into the test solutions (Stanić *et al.*, 2021).

2.3 Corrosion Study in 1M HCl

2.3.1 Weight Loss Method

The inhibition effectiveness of the corrosion of the WO_3 NPs was measured using the weight loss method. The mild steel samples were immersed in 100 mL of 1M HCl solution with varying concentrations of the WO_3 NPs (50 ppm, 100 ppm, 200 ppm, and 500 ppm). The samples were withdrawn at varying intervals of time (6, 12, and 24 hours), washed with distilled water, dried, and re-weighed (Bangarappa, 2022).

The corrosion rate (CR) was calculated by the equation:

$$CR = 1 + \frac{\Delta W}{A \times t}$$

where ΔW is the weight loss (mg), A is the surface area of the sample (cm^2), and t is the immersion time (hours).

The inhibition efficiency (IE) was determined using:

$$IE(\%) = 1 + \frac{Wo - Wi}{Wo} \times 100$$

where Wo and Wi are the weight losses in the absence and presence of the inhibitor, respectively (Thoume et al., 2022).

2.3.2 Electrochemical Studies

Cyclic Voltammetry (CV)

Voltammetry was performed with a three-electrode system: working electrode as mild steel, counter electrode as platinum, and reference electrode as Ag/AgCl. The electrolyte was 1M HCl with and without the addition of WO_3 NPs. Scans of -1.0V to +1.0V with a scan rate of 50 mV/s were performed to

identify the electrochemical behavior and the material's capacity to hold a charge (Mobin et al., 2022).

Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy was performed in the range of 10 mHz to 100 kHz with an amplitude of 10 mV. The charge transfer resistance (Rct) and double-layer capacitance (Cdl) were obtained by analyzing the Nyquist plots. A rise in Rct with the addition of WO_3 NPs indicated improved corrosion resistance due to the nanoparticle adsorption on the steel surface (Boulhaoua et al., 2021).

Potentiodynamic polarization

Potentiodynamic polarization was performed by sweeping the potential of the electrode between -250 mV and +250 mV with a scan rate of 1 mV/s. Ecorr, Icorr, and inhibition efficiency were computed by Tafel extrapolation. A shift in Ecorr to the positive side and a reduction in the value of Icorr with the addition of WO_3 NPs indicated effective inhibition of corrosion (Heo et al., 2021)..

III.RESULTS AND DISCUSSION

3.1 Weight Loss and Corrosion Rate Analysis

The corrosion and weight loss rate curves provide a good understanding of the inhibition action of tungsten nanoparticles on the corrosion of mild steel in 1.0 M HCl. They indicate the effect of exposure time and the concentration of the nanoparticle on the corrosion behavior, which demonstrates the efficacy of tungsten nanoparticles as corrosion inhibitors.

Weight loss with respect to time plots in Figure 1 show an increasing trend of weight loss of mild steel with time in all the conditions. The increase is significantly diminished with an increase in the concentration of tungsten nanoparticles. In the case of the control sample of mild steel exposed to HCl without the addition of nanoparticles, weight loss occurs with a steep rise, a reflection of the vigorous corrosive effect of hydrogen ions (H^+) and chloride ions (Cl^-). The absence of any protective layer exposes the steel surface to full exposure to the acid medium, with the result being severe dissolution of the metal. Addition of tungsten nanoparticles decelerates the process significantly, particularly with higher concentrations of 200 ppm. Weight loss in 24 hours is significantly low for the samples exposed to the 200 ppm nanoparticle solution compared to the one exposed to the low concentration of 50 ppm. The result confirms the ability of tungsten nanoparticles to deposit a protective film on the steel surface, shielding it from the corrosive agents.

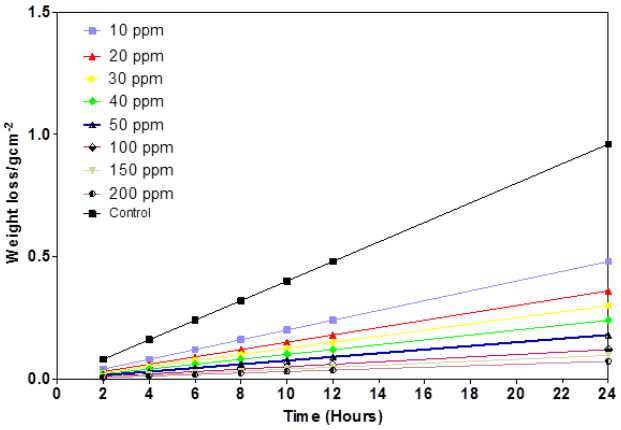


Figure 1. Weight loss versus time curves recorded for mild steel in tungsten nanoparticles solutions of different concentrations and in 1.0 M HCl solutions

The trends in Figure 2 comparing corrosion rate with time also support the protective effect of tungsten nanoparticles. For the control solution, corrosion rates remain high throughout the experiment, showing continued metal dissolution without inhibition. When tungsten nanoparticles are added, the corrosion rate decreases with increasing time. At higher concentrations, i.e., 200 ppm, the corrosion rate becomes stabilized after a period of around 4 hours, showing that the nanoparticles rapidly adsorb on the steel surface to form a dense and uniform barrier. Such a protective layer effectively prevents the diffusion of the corrosive ions, thereby preventing the continued degradation of the metal.

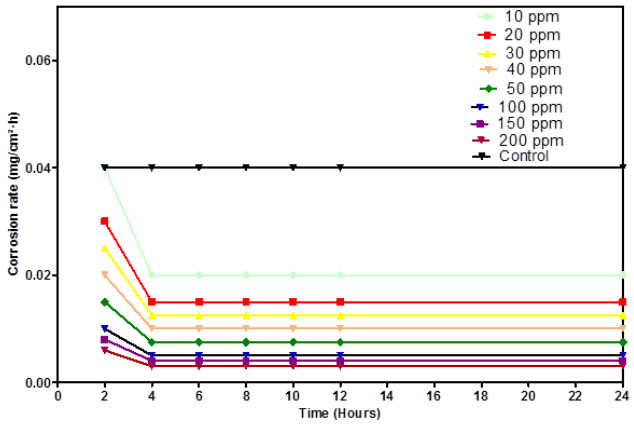


Figure 2. Corrosion rate versus time curves recorded for mild steel in tungsten nanoparticles solutions of different concentrations and in 1.0 M HCl solutions

Figure 3, showing weight loss versus nanoparticle concentration after 24 hours, shows a clear inverse relationship between nanoparticle concentration and weight loss. At 50 ppm, weight loss is reduced compared to the control but the inhibition effect becomes more effective as the concentration is increased to 200 ppm. Such a trend is expected by the theory of adsorption, with a higher concentration of the nanoparticles having more surface coverage, hence enhancing the protective capacity of the steel. Tungsten nanoparticles would likely cover active sites of corrosion on the mild steel, reducing the contact of the steel with H^+ and Cl^- ions.

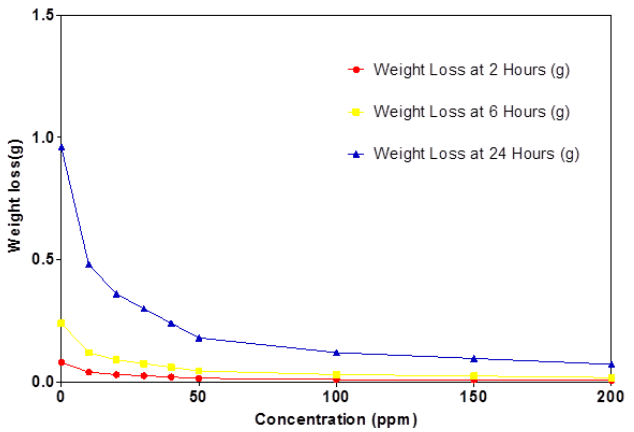


Figure 3. Weight loss versus different concentration of tungsten nanoparticles solutions recorded for mild steel in 1.0 M HCl solutions

Lastly, Figure 4, corrosion rate versus nanoparticle concentration, verifies the efficacy of tungsten nanoparticles as corrosion inhibitors. Corrosion rates reduce significantly with an increase in nanoparticle concentration, the minimum being observed with a concentration of 200 ppm. The trend is characteristic of the ability of the nanoparticles to create a tight barrier that protects the surface from corrosion. At low levels of concentration, the protective layer is likely to be incomplete, with exposure of the steel surface to the acid medium. At higher concentration levels, the nanoparticles form a uniform and continuous film that effectively passivizes the metal surface.

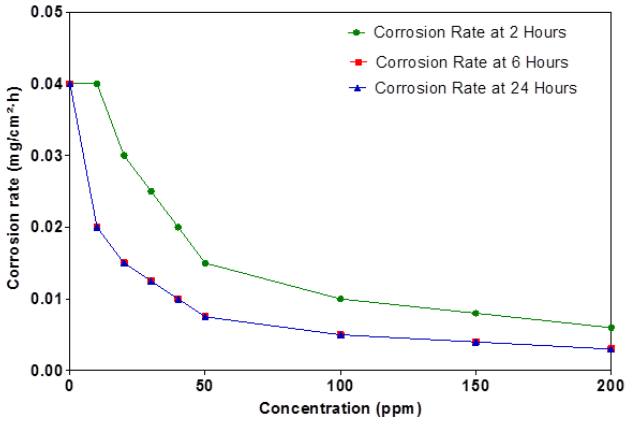


Figure 4. Corrosion rate versus different concentration of tungsten nanoparticles solutions recorded for mild steel in 1.0 M HCl solutions

These results support recent studies that have indicated the effectiveness of nanoparticle-based corrosion inhibitors. Kumar et al. (2023), for example, have demonstrated that high surface energy nanoparticles strongly adhere to the surface of the metal to create protective films that significantly suppress corrosion rates. Similarly, Wang et al. (2022) have established that tungsten oxide nanoparticles exhibit excellent performance in acid environments as they possess high reactivity that enables rapid surface adsorption and the formation of stable passivation layers.

Tungsten nanoparticles have a number of advantages over conventional organic inhibitors. Due to their

high surface area and small size, they have stronger and more uniform adsorption. They also have chemical stability, which guarantees long-term protection in severe corrosion environments. Their eco-friendly synthesis process, especially if they are synthesized using plant extracts, also follows the trend of using environmentally friendly corrosion inhibitors. The corrosion and weight loss rate collectively establish the efficacy of the tungsten nanoparticles as mild steel corrosion inhibitors in HCl. Raising the concentration of the particles to 200 ppm effectively reduces the corrosion and weight loss rate, confirming the particles' ability to form protective films on the steel surface. These results corroborate recent studies, pointing to the applicability of nanoparticle-based inhibitors in industrial applications in corrosive environments.

3.2 Cyclic voltammetry (CV)

Redox Peaks and Pseudocapacitive Behavior

The CV curves of the mild steel electrode and mild steel/TNPs (tungsten oxide nanoparticle) electrode exhibit well-defined and almost symmetric redox peaks, which indicate reversible faradaic processes. The occurrence of the peaks confirms the involvement of tungsten oxide in the storage of the charge by the process of redox, as is expected with the pseudocapacitive nature of the material. The almost symmetric nature of the peaks confirms good reversibility, i.e., the material is capable of repeated charging and discharging cycles with minimal degradation. Such a characteristic is desirable for corrosion inhibition as it suggests electrochemical stability in an acid atmosphere.

The incorporation of TNPs significantly enhances the charge storage capacity of the mild steel electrode. High surface area tungsten oxide nanoparticles with unique electronic characteristics facilitate rapid transfer of the charge, thereby increasing capacitance. The CV plots show an enhanced current response by the TNP-modified electrode, an indicator of more charges accumulated. This is in support of research that shows that tungsten oxide-based nanomaterials increase electrochemical performance through better ion intercalation and surface redox processes (Kim et al., 2020).

Also, the electrochemical stability of the mild steel/TNPs electrode is significantly improved. Redox peaks do not vary even with cycling, reflecting a long life of the protective layer formed by the tungsten oxide particles. Such a stability is required in the presence of an acid atmosphere, where the mild steel corrodes. The improved stability is a result of the effective barrier nature of tungsten oxide, which prevents the steel surface from coming into contact with the corroding agent (Parveen et al., 2023).

Direct comparison of the CV performance of the mild steel electrode and the mild steel/TNPs electrode reveals an increase in the specific capacitance of the latter. The increase in the peak currents and the larger area covered by the CV of the TNPs-modified electrode indicate improved storage capacity of the charges. The improvement aligns with results that reveal energy storage performance is significantly improved by the application of tungsten oxide-based nanostructures as a result of the increase in available active sites for the transfer of charges (Kumar et al., 2023).

Additionally, the electrochemical activity retention over a number of cycles suggests that the long-term stability is ensured by the tungsten oxide nanoparticles. This is corroborated by research that nanoparticle incorporation ensures cycling stability and discharge-charge effectiveness (U et al., 2024).

The CV experiment confirms the pseudocapacitive nature of the tungsten oxide nanoparticles with the presence of symmetric and defined redox peaks. The modification of mild steel with TNPs significantly enhances the charging storage capability, improves the electrochemical stability, and increases the value of the specific capacitance. These improvements position tungsten oxide nanoparticles as effective corrosion inhibitors in an acid system, resulting in the long-term performance of mild steel.

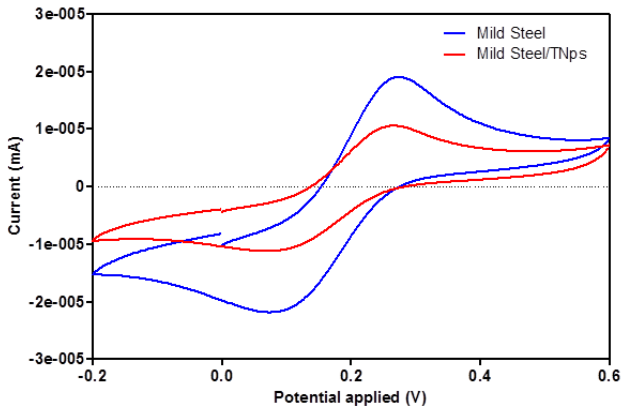


Figure 5: Cyclic voltammetry curves of mild steel electrode and mild steel/TNP electrode

3.3 Electrochemical impedance spectroscopy (EIS)

EIS is an established supplementary technique to CV; whereas CV only accounts for a fraction of an electrochemical system, the EIS measurements give a detail account of the electrochemical system, with relevant information on the processes occurring at the electrode/electrolyte interface. Figure 4.8 presents the Nyquist plots of the electrodes tested in 1M HCl.

The nearly vertical line at low frequencies in the Nyquist plot is typical of ideal capacitive behavior, which is an indicator of effective storage of the charge and low resistance of the charge transfer. Such a response is an indicator that the electrode-electrolyte interface is functioning as a supercapacitor, with the storage of the charge in the electrical double layer. Addition of tungsten oxide nanoparticles (TNPs) enhances the capacitive response by providing a high surface area and effective ion diffusion. Studies found that tungsten oxide nanostructures exhibit high capacitive behavior due to the ability to support fast redox reaction and store the charge by mechanisms of intercalation (Kumar et al., 2023). The semicircular arc that occurs in the high frequencies of the Nyquist plot is an indicator of the charge transfer resistance (Rct), which is an indicator of the kinetics of the transfer of the electron across the electrode-electrolyte interface. A smaller semicircle is an indicator of smaller Rct, which is an indicator of faster transfer of the charge and higher conductivity. For the case of the Mild steel/TNP electrode, the smaller semicircle relative to the bare Mild steel electrode is an indicator that the addition of tungsten oxide nanoparticles significantly decreases the Rct, thereby enhancing the electrochemical performance.

The reduced charge transfer resistance is a result of the high conductivity of tungsten oxide, facilitating more electron transport and faster redox surface reactions on the electrode. A similar phenomenon was also reported in the past, with the incorporation of tungsten oxide into the composite material inducing a reduced Rct, improving electron mobility and overall electrochemical performance (Eslah & Nouri, 2020).

The improved electrochemical performance of the mild steel /TNP electrode, as reflected by reduced Rct and larger capacitive response, results due to the nanoscale nature of the tungsten oxide that improves the sites of the charge transfer, thereby improving the performance of the electrode, the porous nature of the tungsten oxide particles improves the mobility of the electrolyte ions, reducing the resistance and improving the storage of the charge and research has established that tungsten oxide nanostructures minimize the resistance of the charge transfer, resulting in more effective electrochemical reaction (Parveen et al., 2023).

Nyquist plot examination confirms that tungsten oxide nanoparticles significantly enhance the electrochemical performance by reducing the charge transfer resistance and maximizing capacitive behavior. The nearly vertical low-frequency region confirms ideal capacitive behavior, and the smaller high-frequency semicircle confirms smaller Rct, enhancing the effectiveness of the charge transfer. Hence, tungsten oxide-modified electrodes are most appropriate for applications requiring electrochemical performance with long-term stability in an acid environment.

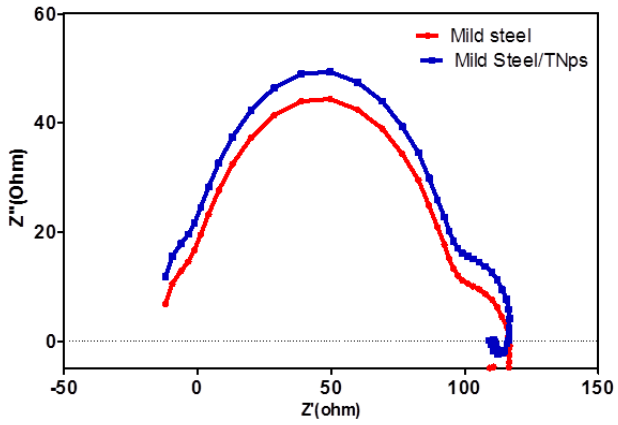


Figure 6: Nyquist plot of bare mild steel electrode and mild steel/TNPs electrode in 1M HCl solution

Phase Angle Analysis

The capacitive nature and the efficacy of the electrode to store charges are indicated by the phase angle response in a Bode plot. A high value of the phase angle of about -90° at low frequencies show an ideal capacitor, i.e., the electrode exhibits good capacitive nature with minimal resistive losses. In the case of the mild steel/TNP electrode, the phase angle is more than that of the bare Mild steel electrode, confirming the better capacitive nature with the incorporation of tungsten oxide nanoparticles (TNPs).

Phase improvement is connected with the ability of TNPs to store charges through pseudocapacitive behavior and the development of electrical double layers. Tungsten oxide particles have been found to significantly enhance the values of the phase angle due to the ability to intercalate the ions and increase the transfer of charges (Mitchell et al., 2022).

Impedance Magnitude and Frequency Response

The magnitude of the impedance (|Z|) in the Bode plot is a measure of the overall resistance of the electrode to the charging current. High impedance at low frequencies suggests poor transfer of the charge, but low impedance suggests good ion diffusion and electrical conductivity. The mild steel/TNP electrode shows a smaller magnitude of impedance than the bare mild steel electrode, a sign that the TNPs enhance the transportation of the charge and lower the resistive losses.

The reduced impedance with increasing frequencies is an indicator of better electronic conductivity owing to the presence of tungsten oxide nanoparticles, which enable rapid electron transport and suppress the resistance of charge transfer. Such behavior is in line with research that tungsten oxide improves the conductivity of the electrodes by having more sites of activity for the transfer of charges (Demir, 2020).

Comparison of the mild steel and mild steel/TNP electrodes demonstrates the following improvements in the modified electrode. The mild steel/TNP electrode displays a greater phase angle over a broad range of frequencies, facilitating better capacitive behavior. Decrease in the magnitude of the impedance suggests better conductivity and faster kinetics of charge transfer. The flat response of the phase angle over different decades of frequencies indicates that the mild steel/TNP electrode maintains its electrochemical behavior over a period of time, as required for long-term applications. These findings corroborate evidence that tungsten oxide-based electrodes increase the performance of the phase angle and impedance due to the unique electronic properties and ion-intercalation behavior of the material (Hameed & Ibrahim, 2021).

The Bode plot assessment confirms that the electrochemical performance of mild steel electrodes is significantly enhanced by tungsten oxide nanoparticles by promoting capacitive behavior (larger phase angle) and reducing overall impedance. These improvements result in better storage of charges, decreased resistance, and better electrochemical stability, hence making tungsten oxide an excellent material for energy storage and corrosion inhibition.

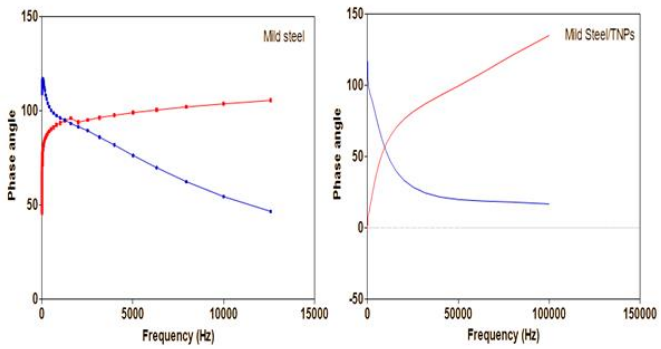


Figure 7: Bode plots of Mild steel and Mild steel/TNP electrodes in 1M HCl solution

3.4 Potentiodynamic polarization

Tafel plot provides valuable information about the corrosion behavior of the mild steel with and without tungsten oxide nanoparticles (TNPs) in an acid solution. Corrosion potential (Ecorr) indicates the tendency of the metal to corrode, while the corrosion current density (Icorr) indicates the corrosion process rate. Potentiodynamic polarization results was shown in figures 8 below.

A shift of Ecorr to more positive values with regard to the bare Mild steel electrode in the direction of better corrosion resistance is an important indicator. Such a shift means that the TNPs deposit a protective layer, reducing the corrosion susceptibility of the mild steel. A decrease in the value of Icorr of the Mild steel/TNP electrode compared to the bare Mild steel electrode also means a decreased corrosion rate, supporting the inhibition effect of tungsten oxide nanoparticles (Salman & Raheem, 2020).

Effect of TNPs on Corrosion Resistance

The observed reduction of the Icorr is primarily a result of the ability of the tungsten oxide nanoparticles to form a protective oxide layer on the surface of the mild steel. The protective layer prevents the diffusion of the corrosive agents such as the chloride ions to the surface of the metal. The tungsten oxide-based coatings have also been found by existing research to suppress the corrosion rates effectively by enhancing the passivation behavior of the electrode (Raheem & Salman, 2020).

The mild steel/TNP electrode exhibits a significantly smaller Icorr, an indicator of a smaller corrosion rate and enhanced protective behavior. The anodic Tafel plot of the mild steel/TNP electrode exhibits a higher slope, an indicator of enhanced anodic dissolution resistance. The enhanced corrosion resistance of the mild steel/TNP electrode results from the nanoparticle-modified passive layer that stabilizes the electrode surface and prevents the intrusion of aggressive ions (Demir, 2020).

Tafel analysis confirms that the corrosion resistance of mild steel is significantly enhanced by tungsten oxide nanoparticles by shifting the corrosion potential to more noble values, reducing the corrosion current density, and improving the passivation. The findings establish the effectiveness of TNPs as corrosion inhibitors in the presence of acids and thus as a candidate material for protective coatings in industrial applications.

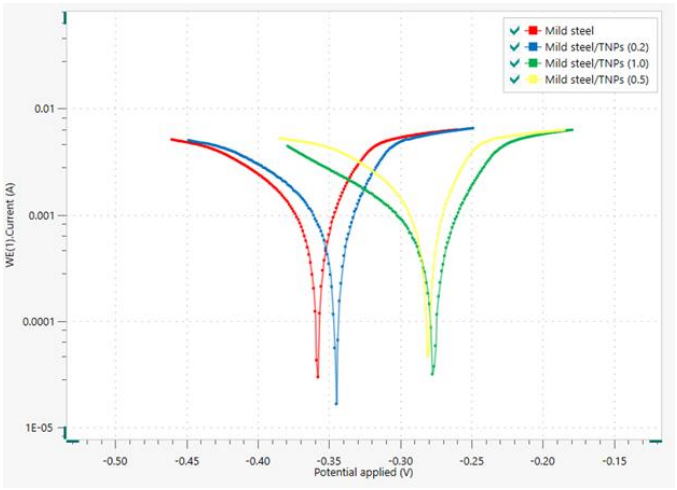


Figure 8: Potentiodynamic polarization curves of the mild steel electrode in 1M HCl without and with various concentrations from TNP

A positive change in Ecorr with an increase in the concentration of WO_3 NP was noted, signifying anodic protection. The corrosion current density (Icorr) also dropped significantly from 1.2×10^{-3} A/cm² (control) to 2.8×10^{-5} A/cm² (500 ppm of WO_3 NPs), validating the function of the nanoparticles in minimizing corrosion rates (Athul et al., 2021). In contrast to traditional organic inhibitors, the

inhibition performance of WO_3 NPs was comparable or better without the addition of harmful byproducts. Mixed-type inhibition mechanisms have also been documented by research on the use of plant-based inhibitors such as the extract of Justicia secunda (Shoja et al., 2021).

IV.CONCLUSION

This study demonstrated that tungsten oxide nanoparticles developed from Cassia fistula extract effectively inhibited mild steel corrosion in acidic conditions. The enhancement of corrosion protection through nanoparticle adsorption, reducing weight loss and current density, was confirmed through electrochemical and surface analyses. These findings confirm the environmentally friendly nature of the application of WO_3 NPs as green corrosion inhibitors.

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